

Gamma-ray emission from strongly magnetized pulsars

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ABSTRACT

In a strong magnetic field, $B \gtrsim 4 \times 10^{12}$ G, γ -rays emitted nearly along curved field lines adiabatically convert into bound electron-positron pairs (positronium atoms) rather than decaying into free pairs. This process may modify the polar gaps of strong magnetized pulsars. Unlike free pairs, such bound pairs do not screen the electric field component along the magnetic field in the polar gaps. As a result the total power carried away by both relativistic particles and radiation, from the polar gap into the pulsar magnetosphere, may increase significantly (up to a few tens times) in comparison with the conventional polar gap models where creation of bound pairs is ignored, and it may be a substantial fraction of the spin-down power. We demonstrate that the total power of the modified polar gaps may be enough to explain the observed non-thermal luminosities of all known strongly magnetized, γ -ray pulsars.

Subject headings: gamma rays: theory — pulsars: general — radiation mechanisms: non-thermal

1. Introduction

After the *Compton Gamma Ray Observatory (CGRO)* ended its activity in 2000, seven rotation-powered γ -ray pulsars were known (e.g., Thompson et al. 1997). More recently, the *AGILE* telescope reported the detection of two other radio pulsars in γ -rays. The *Fermi Gamma-ray Space Telescope* was successfully launched in 2008. After two years of observations by *Fermi*, the number of known γ -ray pulsars increased dramatically, to more than sixty, and continue increase (Ray & Saz-Parkinson 2010). For known γ -ray pulsars the maximum

of the radiated power is concentrated in the γ -ray range, except for the Crab pulsar and PSR B1509-58, the power of which peaks in hard X-rays. The pulsar luminosities L_γ in γ -rays are a substantial fraction of the spin-down power, $\eta_\gamma = L_\gamma/\dot{E}_{\text{rot}} \sim 10^{-2} - 1$ (Abdo et al. 2010), where $\dot{E}_{\text{rot}} = 4\pi^2 I \dot{P} P^{-3}$ is the spin-down power, I is the moment of inertia of the neutron star (generally taken to be 10^{45} g cm^2), P its spin period, and \dot{P} its spin-down rate.

The starting point common to all viable models of pulsars is that strong electric fields are generated in the magnetospheres of rotating neutron stars (e.g., Michel 1991). The electric field component, $E_\parallel = (\mathbf{E} \cdot \mathbf{B})/|\mathbf{B}|$, along the magnetic field, \mathbf{B} , is non-zero and may accelerate particles to ultrarelativistic energies. The accelerated particles emit γ -rays due to curvature emission and other processes. Some of the γ -rays are converted into e^+e^- pairs in a strong magnetic field. The pairs screen the field E_\parallel in the pulsar magnetosphere everywhere except for some compact regions called "gaps". These gaps are, in fact, "engines" responsible for the non-thermal radiation of pulsars.

Three kinds of gaps have been proposed in trying to explain the non-thermal radiation of pulsars. The main difference between these is in the site of gaps. A gap that forms near the magnetic pole of a pulsar is called a polar gap (Ruderman & Sutherland 1975). Besides, an outer gap may form between the surface of null Goldreich-Julian density and the light cylinder (Cheng, Ho, & Ruderman 1986a,b). The third possibility is a slot gap located in the space-charge-limited flow along the last closed field line (Arons 1983; Muslimov & Harding 2004).

In conventional models of polar gaps, it is assumed that created e^+e^- pairs are free (Ruderman & Sutherland 1975; Daugherty & Harding 1982, 1996; Medin & Lai 2010 and references therein). However, this assumption is not valid if the magnetic field is higher than $\sim 0.1 B_0 \simeq 4 \times 10^{12} \text{ G}$, where $B_0 = m^2 c^3 / e \hbar = 4.4 \times 10^{13} \text{ G}$. The reason is that in such a strong field, γ -rays emitted nearly along the curved field lines, adiabatically convert into bound electron-positron pairs (positronium) rather than decaying into free pairs (Shabad & Usov 1985, 1986; Herold et al. 1985; Usov & Melrose 1995, 1996; Baring & Harding 2001; Harding & Lai 2006; Thompson 2008). The fact that e^+e^- pairs created in a magnetic field $B > 0.1 B_0$ are bound, may be very important for the observational appearances of strongly magnetized pulsars (Usov & Melrose 1995). In particular, unlike free pairs, such bound pairs do not screen the electric field E_\parallel near the pulsar, which requires a net charge density to build up. As a result the pulsar luminosity is higher than it would have been if the created pairs are free. For pulsars with strong surface magnetic fields, $B_s > 0.1 B_{\text{cr}}$, a polar gap is modified by taking into account creation of bound pairs as was suggested by Usov & Melrose (1995, 1996). In this model, the total power carried away by both relativistic particles and radiation, from the polar gap into the magnetosphere, may increase significantly (up to a

few tens times) in comparison with the conventional polar gap models, and it may be a substantial fraction of the spin-down power. In this Letter, we demonstrate that the total power of the modified polar gaps may be enough to explain the observed luminosities of all known strongly magnetized, γ -ray pulsars. Other observational consequences of the modified polar gap model for these pulsars are also discussed.

2. Radiative efficiency

In the modified polar gap model (Usov & Melrose 1985, 1986), the fraction of the spin-down power carried away by both relativistic particles and radiation from the polar gap into the magnetosphere is estimated as

$$\eta_\gamma^b = \frac{L_p^b}{\dot{E}_{\text{rot}}} \simeq \frac{3}{2} \left(\frac{P}{P_1} \right)^{3/2} \left[1 - \left(\frac{P}{P_1} \right)^{3/2} \right]. \quad (1)$$

where $P_1 \simeq 0.5(B_p/0.1B_0)^{2/3}$ s, and B_p is the magnetic field strength at the poles. At $P = 2^{-2/3}P_1 \simeq 0.63P_1$, the value of η_γ^b is maximum, $\eta_\gamma^b|_{\text{max}} = 3/8 = 0.375$. In this case the polar gap luminosity L_p^b is comparable with the spin-down power.

The modified polar gap model is valid if both $B_p > 0.1B_0$ and $P_2 < P < P_1$ (Usov & Melrose 1986), where

$$P_2 \simeq 0.07(T_s/10^6 \text{ K})^{4/11}(B_p/0.1B_{\text{cr}})^{2/11} \text{ s}. \quad (2)$$

For γ -ray pulsars satisfied these conditions, measured and derived properties are given in Table 1. Additionally, the parameters of two γ -ray pulsars (J0633+1746 and J1057-5226) are included in Table 1. In these two cases, the observed efficiency of transformation of the spin-down power into the non-thermal high-frequency emission is very high, $\eta_\gamma^{\text{obs}} = L_{\gamma+X}/\dot{E}_{\text{rot}} \sim 1$, while the dipolar B-field estimate is only slightly below the value required for bound-pair formation. The surface magnetic field may be higher than the dipolar estimate and satisfies the requirement of bound-pair formation, $B_p \geq 0.1B_0$, provided one invokes higher-order multipolar components, or an off-centered dipole. To estimate the possible value of η_γ^b for these two pulsars we take $B_p = 0.1B_0 = 4.4 \times 10^{12}$ G (see the second lines in Table 1).

From Table 1 we can see that the predicted value of η_γ^b is about or more than the minimum observed value of the radiative efficiency, η_γ^{obs} , for all strongly magnetized γ -ray pulsars except of PSR J2021+4026. It is worth to note that the γ -ray luminosities of pulsars given in Table 1 were only roughly estimated by Abdo et. al. (2010) using the following

equation

$$L_\gamma = 4\pi d^2 f_\Omega G, \quad (3)$$

where d is the distance of the pulsar, G is the average energy flux in γ -rays, and f_Ω is the flux correction factor that takes into account the angular anisotropy of the γ -ray emission of pulsars. The value of f_Ω is model-dependent and varies from ~ 1 in the outer gap and slot gap models to $\sim 1/4\pi \simeq 0.08$ in the polar gap model (e.g., Thompson et al. 1994). Abdo et al. (2010) have used $f_\Omega = 1$ throughout the paper, and therefore, the γ -ray luminosities may be overestimated at least a few times. Summarizing, the power carried away by both relativistic particles and radiation from the modified polar gaps into the magnetosphere may be sufficient to explain the non-thermal luminosities of all known strongly magnetized γ -ray pulsars, including PSR J2021+4026.

For comparison, in conventional polar-gap models, where the created pairs are assumed to be free, the corresponding fraction of the spin-down power going into both high-energy particles and radiation may be estimated as (e.g., Usov & Melrose 1995)

$$\eta_\gamma^f = \frac{L_p^f}{\dot{E}_{\text{rot}}} \simeq 1.5 \times 10^{-3} \left(\frac{B_p}{0.1 B_0} \right)^{-8/7} \left(\frac{P}{0.1 \text{ s}} \right)^{15/7}. \quad (4)$$

From Table 1 we can see that η_γ^f is more than an order of magnitude smaller than η_γ^{obs} except for a few γ -ray pulsars. Even taking into account the uncertainty in η_γ^{obs} because of the uncertainty of f_Ω , we can see that for the main part of the strongly magnetized γ -ray pulsars the inferred high efficiency of conversion of rotational energy into γ -ray radiation cannot be explained within the conventional polar-gap models.

For six pulsars the observed luminosities in γ -rays are not presented in Table 1 because their distances are unknown. Equalizing η_γ^{obs} to η_γ^b for these pulsars, upper limits on the distances may be estimated in the frame of the modified polar gap model.

3. Spectrum of γ -rays

The γ -ray spectra of pulsars were fitted by an exponentially cutoff power-law model, $dN/dE \propto E^{-\alpha} \exp(-E/E_{\text{cutoff}})$, with the photon index α in the range 0.7-2.4 and the cutoff energy E_{cutoff} at 0.1-7 GeV (Abdo et al. 2010, Pilia et al. 2010). These spectra may be explained by curvature radiation of high-energy electrons that escape from the polar caps with the Lorentz factor $\Gamma \sim 10^7$ (Harding 1981, Daugherty & Harding 1982; Chiang & Romani 1992). The value of $\Gamma \sim 10^7$ is more or less appropriate for primary electrons at the top edge of the polar gap in the conventional polar gap models, in which the density

of primary particles is slightly smaller than the Goldreich-Julian density n_{GJ} (Goldreich & Julian 1969; Ruderman & Sutherland 1975; Arons 1981). To explain the luminosities of γ -ray pulsars, it was suggested by Harding (1981) that the density of the outflowing electrons with Lorentz factor $\Gamma \sim 10^7$ is $\sim (10^2 - 10^3)n_{\text{GJ}}$. Although this suggestion is inconsistent with the conventional polar gap models, it may be consistent with the modified polar gap model (Usov & Melrose 1995, 1996). Indeed, inside the modified polar gaps the primary electrons are accelerated by the electric field $E_{\parallel} \simeq E_{\parallel}^{\text{ion}}$ to the Lorentz factor $\Gamma_{\text{prim}} \simeq (2 - 3) \times 10^8$ and generate very hard γ -rays via curvature radiation, where $E_{\parallel}^{\text{ion}} \simeq (1 - 2) \times 10^{10}$ V/cm is the electric field at which field ionization of bound pairs becomes important. These γ -rays are absorbed in the magnetic field and create secondary electron-positron pairs with the mean Lorentz factor and the density

$$\Gamma_s \simeq 10^7 \left(\frac{P}{0.1 \text{ s}} \right)^{1/4} \quad \text{and} \quad n_s \simeq 4 \times 10^2 \left(\frac{P}{0.1 \text{ s}} \right)^{-3/4} n_{\text{GJ}}, \quad (5)$$

respectively (Usov & Melrose 1996). The parameters of the secondary particles are well consistent with those suggested by Harding (1981) to explain both the luminosities and spectra of γ -ray pulsars.

In the frame of the conventional polar gap models, it was argued that photon splitting, $\gamma + B \rightarrow \gamma' + \gamma'' + B$, and magnetic absorption of photons, $\gamma + B \rightarrow e^+ + e^- + B$, have to reduce the cutoff energy E_{cutoff} for strongly magnetized γ -ray pulsars, $B_p \gtrsim 10^{13}$ G (Harding et al. 1997; Baring & Harding 2001; Baring 2004). This is consistent with the observational data on PSR B1509-58 that has one of the highest magnetic fields, $B_p \simeq 3.1 \times 10^{13}$ G, and the softest spectrum with a cutoff at $E_{\text{cutoff}} = 81 \pm 20$ MeV. The second softest γ -ray spectrum with $E_{\text{cutoff}} = 0.7 \pm 0.5$ GeV is that of PSR B0656+14, recently observed by *Fermi*. This pulsar has a rather strong magnetic field, $B_p \simeq 0.93 \times 10^{13}$ G, and its soft γ -ray spectrum may be explained in the same way. At present, however, there are a handful of γ -ray pulsars with surface magnetic fields higher than that at the surface of PSR B0656+14, while their γ -ray emission is present to at least a few GeV. One such pulsar is LAT PSR J0007+7303, in the supernova remnant CTA 1. This pulsar has one of the hardest γ -ray spectra with $E_{\text{cutoff}} = 4.6 \pm 0.4$ GeV, while the magnetic field at its poles is $B_p \simeq 2.2 \times 10^{13}$ G, which is only slightly smaller than the B_p -value for PSR B1509-58. Among other pulsars with hard ($E_{\text{cutoff}} > \text{a few GeV}$) γ -ray spectra and strong ($B_p > 0.1B_0$) magnetic fields are PSR J0631+1036, J0633+1746, J1709-4429, and J2021+4026. Since one expects strong absorption of hard γ -rays in the vicinity of these pulsars (Harding et al. 1997, Baring 2004), it is concluded that (1) a polar gap model is inconsistent with the available data on the strongly magnetized γ -ray pulsars with hard γ -ray spectra, and (2) the γ -ray emission of these pulsars arises largely in the outer magnetosphere (e.g., Abdo et al. 2010; Michelson, Atwood, & Ritz 2010).

However, these conclusions may be premature at least for some strongly magnetized γ -pulsars. Indeed, in the modified polar gap model γ -rays generated near the surface of a strongly magnetized pulsar adiabatically convert into bound e^+e^- pairs. If the photoionization of the bound pairs is small, these pairs mostly flow away from the pulsar vicinity and may annihilate at large distances generating hard γ -rays that escape from the pulsar magnetosphere. In other words, bound pairs may be an intermediate agent that transfers γ -rays from the pulsar vicinity to the outer magnetosphere where their absorption is negligible.

The surface temperature of PSR B1509-58 may be as high as $\sim 2 \times 10^6$ K. Besides, this pulsar is a powerful ($L_X \simeq 10^{35}$ erg/s) source of soft X-rays with a non-thermal (power-law) spectrum. The soft X-ray and γ -ray pulses are phase-aligned, indicating that they are generated in the same region in the pulsar magnetosphere (near the magnetic poles in the polar gap model). Most probably, the bound pairs are mostly ionized by both thermal and non-thermal X-rays before leaving the vicinity of PSR B1509-58. In this case, the formation of bound pairs does not affect the conclusion of Harding et al. (1997) that in the polar gap model the γ -ray spectrum of PSR B1509-58 is expected to be very soft. As to PSR J0007+7303, there is an upper limit of $T_S < 6.6 \times 10^5$ K (Halpern et al. 2004). Recently, Caraveo et al. (2010) decreased the upper limit on the surface temperature of PSR J0007+7303: $T_S < 5.3 \times 10^5$ K, that is one of the most constraining data points on cooling models of neutron stars. This makes PSR J0007+7303 by far the coldest neutron star for its age interval, suggesting the necessity of enhanced neutrino emission for this rather young γ -ray pulsar (Page, Geppert, & Weber 2006; Caraveo et al. 2010). The surface temperature of PSR J0007+7303 in the cooling model of neutron stars with enhanced neutrino emission may be as low as $(1 - 2) \times 10^5$ K (Page et al. 2006). For this temperature, the bound pairs may leave the pulsar vicinity and annihilate far from the pulsar into hard γ -rays, $\varepsilon_\gamma \gtrsim$ a few GeV.

4. Discussion

In this paper, we have demonstrated that the observed non-thermal luminosities of strongly magnetized pulsars may be explained in the polar gap model modified by taking into account the process of adiabatical conversion of γ -rays into bound electron-positron pairs in a strong magnetic field, $B \gtrsim 4 \times 10^{12}$ G. The high-energy spectra of γ -ray pulsars may be also explained by the modified polar gap model. However, all available polar gap models have difficulty in reconciling the observed γ -ray pulses with the known radio pulsar geometry. At present, it is not clear possible or not to overcome this difficulty in the modified polar gap model at least for some strongly magnetized pulsars.

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Table 1: Properties of γ -ray pulsars

PSR	P (ms)	B_p (10^{12}G)	Age (kyr)	\dot{E}_{rot} (10^{34}erg s^{-1})	$L_{\gamma+X}$ (10^{34}erg s^{-1})	$\eta_{\gamma}^{\text{obs}}$ (10^{-2})	η_{γ}^f (10^{-2})	η_{γ}^b (10^{-2})
J0007+7303	316	22	14	45.2	8.9 ± 3.8	20 ± 8	0.28	14
J0248+6021	217	7	63	21	$1.5 - 30$	$7 - 140$	0.46	22
J0357+32	444	4.7	590	0.5	—	—	3.4	25
J0631+1036	288	11	44	17.3	$0.2 - 4.8$	$1 - 27$	0.51	22
J0633+0632	297	10	59	11.9	—	—	0.6	24
J0633+1746	237	3.3	340	3.3	$2.5^{+2.4}_{-1.2}$	78^{+74}_{-38}	1.1	—
	...	(4.4)	...	...	...	...	1	33
J0659+1414	385	9.3	110	3.8	0.031 ± 0.008	1 ± 0.2	1.1	33
J1048-5832	124	7	20	201	15 ± 9	8 ± 5	0.14	11
J1057-5226	197	2.2	540	3.0	1.7 ± 0.9	56 ± 31	1.2	—
	...	(4.4)	...	...	...	...	0.64	28
J1124-5916	135	20	3	1190	$10^{+3.4}_{-5.4}$	$1^{+0.3}_{-0.4}$	0.05	4.2
J1418-6058	111	8.8	10	498	$11 - 70$	$2 - 14$	0.08	7.4
B1509-58	150	31	1.7	1800	39 ± 14	2.2 ± 0.8	0.04	3.4
J1709-4429	102	6.3	18	341	$29 - 190$	$9 - 57$	0.1	9
J1732-31	197	4.6	120	13.6	—	—	0.61	27
J1741-2054	414	5.4	390	0.9	0.22 ± 0.13	24 ± 14	2.5	36
J1809-2332	147	4.6	68	43	$2 - 28$	$4.6 - 66$	0.33	19
J1826-1256	110	7.4	14	358	—	—	0.1	8.6
J1958+2846	290	16	21	35.8	—	—	0.34	16
J2021+3651	104	6.4	17	338	$1 - 75$	$0.3 - 22$	0.1	9.2
J2021+4026	265	7.7	77	11.6	26 ± 15	220 ± 130	0.64	26
J2238+59	163	8.1	26	90.3	—	—	0.21	14